TO THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

FINAL TECHNICAL REPORT

NGL 05-002-114

SUBMILLIMETER AND MILLIMETER OBSERVATIONS OF SOLAR SYSTEM OBJECTS

from

California Institute of Technology
Pasadena, California 91125

Principal Investigator

Duane O. Muhleman

July 7, 1990

This grant covered the period from about November 1972 through September 1989
This report covers the period 1986-1989

(NASA-CR-[illegible]) SUBMILLIMETER AND MILLIMETER OBSERVATIONS OF SOLAR SYSTEM OBJECTS Final Technical Report, 1986 - 1989 (California Inst. of Tech.) 13 p CSCL 03A — N90-26731
Unclas G3/89 0287123

Personnel:

Professor D.O. Muhleman
Dr. Glenn Berge
Kathryn Pierce
Arie Grossman

INTRODUCTION

This grant supported microwave spectroscopy of solar system objects. It necessarily involves millimeter and submillimeter wavelengths where rotational transitions reside. This field should be regarded as "new" even though NASA provided funds to build a millimeter wave telescope at the University of Texas nearly 30 years ago for this purpose. The existing national facilities are at OVRO, the 12-meter at Kitt Peak, UC array at Hat Creek, the Caltech CSO on Mauna Kea, and the 14-meter at the Univ. of Massachusetts, near Amherst. Our group used all of these instruments in the last year except the Univ. of Massachusetts 14-meter. While these are all heavily used in astrophysics, the number of planetary astronomers involved do not exceed about 5! Nevertheless, this wavelength range (0.3 to 3 mm) is about to enjoy an explosion of interest as submillimeter receivers become better and easier to use. This region of the spectrum is rich in transitions of molecules that exist in the planetary atmospheres which can be studied for temperature-pressure profiles, wind tracers, and atmospheric chemistry.

The Caltech microwave group has been aggressive about planetary microwave spectroscopy, including the training of Ph.D.'s (Pete Schloerb, Todd Clancy, Kathryn Pierce, and several younger people). In recent years, these funds have been primarily used for travel to observatories and subsistence while in residence. The current funding basically supports one graduate student, Kathryn Pierce, who should complete her degree about one year from now. We find that the limiting factors on our millimeter spectroscopy work are travel funds to observatories and student stipends. However, our current level of work is productive. A younger student will replace Pierce next year. It should be clear from this discussion that we believe that the planetary astronomy community is not yet aware of the power of these techniques. This will become more obvious as both the arrays at OVRO and Hat Creek are increased from 3 telescopes to 6 during the next year or so. Furthermore, the National Radio Astronomy Observatory is submitting a proposal to the NSF to build a millimeter wave VLA. It is vital to keep the pioneering work and the training of students (and research fellows) going at a healthy pace.

The list of solar system objects that have been recently addressed with these techniques include:

1) Venus: CO studies of T–P profiles, winds, and photochemistry. SO_2 detections. Continuum mapping remains to be done at 1 mm.
2) Earth: H_2O, CO, NO, NO_2, $O^{18}O$, etc. as a test bed for other atmospheres.
3) Mars: H_2O, CO, $O^{18}O$ studies of T–P profiles, winds (fall of 1990), and photochemistry
4) Saturn: Same as Jupiter plus submillimeter and millimeter mapping of the ring system.
5) Uranus & Neptune: Continuum thermal mapping
6) Titan: CO, HCN, and HC_3N T–P information and photochemistry

Nearly all of this list can be addressed with the OVRO array upgraded to 6 telescopes with in two years. This grant supports somewhat less than half of the Caltech planetary microwave spectroscopy. The remainder comes from the PI's NSF grant. The NSF astrophysics program primarily directs their funding towards building and operating these facilities. However, funding for the making of solar system observations is hard to get from that agency. The total NSF planetary astronomy budget is considerably less than that of the NASA Planetary Astronomy Program.

RECENT RESULTS

Venus

We carried out two major observational program using the CO (0–1) rotational transition with the OVRO millimeter 3-element array. During the time of inferior conjunction of 1986, we mapped the 2.6 mm CO absorption line with 4 arc sec resolution in 32 channels with resolution of 1 MHz. The disk diameter was 40 arc sec, the morning terminator was visible and the sub-Earth point on Venus was about at 3 hours local time. The observations required two changes of the antenna configurations and generated 9 baselines for the image formation. An image is shown in Figure 1 where instead of plotting a brightness temperature, the entire CO spectrum for each cell is plotted. The center of the map (0,0) is the point at 3 hours local time, the east limb at 9 hours and the west limb at about 21 hours. The line depths vary with local time, being deepest shortly after midnight and nearly vanishing on the morning limb. This phenomenon is better illustrated in Figure 2 where we show the spectra in a strip along the equator where the morning terminator (6 hours) is at about 9 arc sec east. The absorption lines are deepest at about –4 arc sec. To first order, the depth of the CO lines is a measure of the high altitude mixing ratio of the gas and we are seeing the midnight bulge of carbon monoxide. The work shown here was done by the PI, Dr. A. Grossman, Dr. D. Rudy, and Dr. Glenn Berge. Some of the results have been presented at conferences and not yet in the open literature.

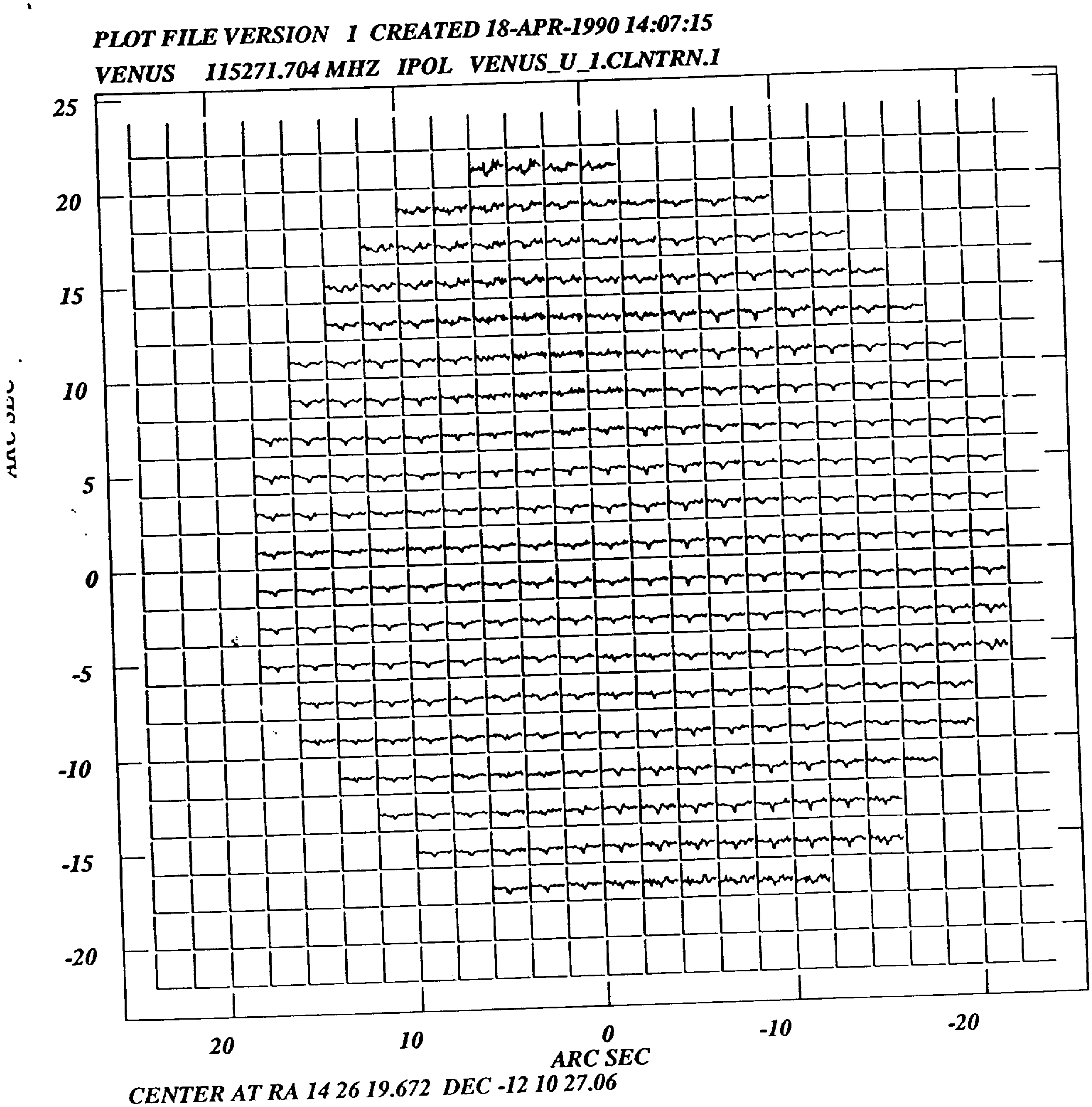
The second experiment was done at the inferior conjunction of Venus in 1988 when the evening terminator was visible from the Earth (preconjunction). The experiment was similar to the one done in 1986 except that spectra were measured in 32 channels with 0.05 MHz resolution in addition to the 32 channels at 1 MHz, thus enabling us to accurately measure the Doppler shifts due to winds in the Venus atmosphere. Model weighting functions show that the effective altitude level is about 98 km. These data are being analyzed by K. Pierce as part of her Ph.D. thesis. The sub-Earth point for this experiment has at a local time of 19.3 hours (7:20 PM). The cores of the CO absorption lines along the equator as a function of local time are shown in Figure 3 where it is obvious that moist of the variation in line depth occurs in the center 2 MHz and, consequently, at very high altitudes. A careful inspection of the spectra in Figure 3 reveals the Doppler shifts. Measurements of the line of sight wind speed from the Doppler shifts over local time of day for 3 latitude strips is shown in Figure 4. A simple, constant retrograde zonal wind would appear as an S-curve with a blue shift at the west limb as the CO approaches and a red shift at the east limb. That is what we see in Figure 4 to first order. The Doppler shifts for pixels on the Venus limbs are direct measurements of the winds — since either zonal or subsolar to antisolar winds are certainly horizontal. The raw measured numbers taken from the map of spectra for such limb cells are shown in Figure 5. While the Doppler shifts of individual spectra can be found to ±10 meters/sec, one can see from this limb map that bigger spectrum-to-spectrum variations exist due to a combination of wind variations on Venus and artifacts that were created in the supersynthesis imaging process. So far, it is obvious that the mean winds are zonal with a mean value of about 98 meters/sec. An examination of the line formation weighting functions tell us that these measured winds refer to about a one-scale height layer centered at an altitude of 98 km. More work will show that the effective altitudes of the measured winds on the night side are slightly higher and those on the day side lower. Pierce has yet to complete that aspect of the analysis and the wind data has yet to be thoroughly studied for a component of wind from the subsolar point to the antisolar point, predicted by Dickerson and Ridley from general circulation models for altitudes well ABOVE 100 km. Their models are consistent with the Pioneer Venus Orbiter data taken near the 150 km level.

Single dish observations: Clancy and Muhleman have continued their systematic observations of Venus and Mars in the carbon and oxygen isotopes of CO. By using the combinations of measurements in the (0–1) and (1–2) transitions, $C^{16}O$, $C^{18}O$, and ^{13}CO, it is possible to cover a considerable range of optical depths in these atmospheres as the center of these lines vary in altitude sampling (Clancy and Muhleman, Global changes in the 0–70 km thermal structure of Mars, *J. Geophys. Res.*, in press; Clancy and Muhleman, Long term (1979–1990) changes in the thermal, dynamical and compositional structure of the Venus mesosphere inferred from microwave spectral line observations of ^{12}CO, ^{13}CO, and $C^{18}O$, submitted to *Icarus*). A few of the results from this work are shown in Figure 6. The top panel shows the mixing profiles inferred from the Kitt Peak, 12-meter spectra for 1986 with the enormous variation at 100 km and above. These results were suggested in Dr. Clancy's thesis work, fully discovered with the OVRO array work in 1986 and are the results of fits to the single dish spectra. The middle panel shows the contrast with the evening face of Venus. The differences in these curves contain the information on the mesospheric circulation of the Venus atmosphere that we are trying to understand! Simultaneous with estimating the CO mixing ratios, we must estimate the temperature profile, shown in the bottom panel of Figure 6. Many believe that the Venusian temperature profile was measured once and for all with the 5 PV entry probes. Figure 6 shows that the mesosphere of Venus is far more dynamic than that of the Earth's and cautions us that vast models built on single encounters of spacecraft with Venus may have very poor predictive value. Mars is a more difficult object because it is further away and because the atmosphere is sufficiently thin enough that we must also deal with the surface emission. There too, we find interesting temperature variations but we await the high-spatial resolution synthesis in the fall to better understand the wind field and the temperature structure of that atmosphere.

Titan

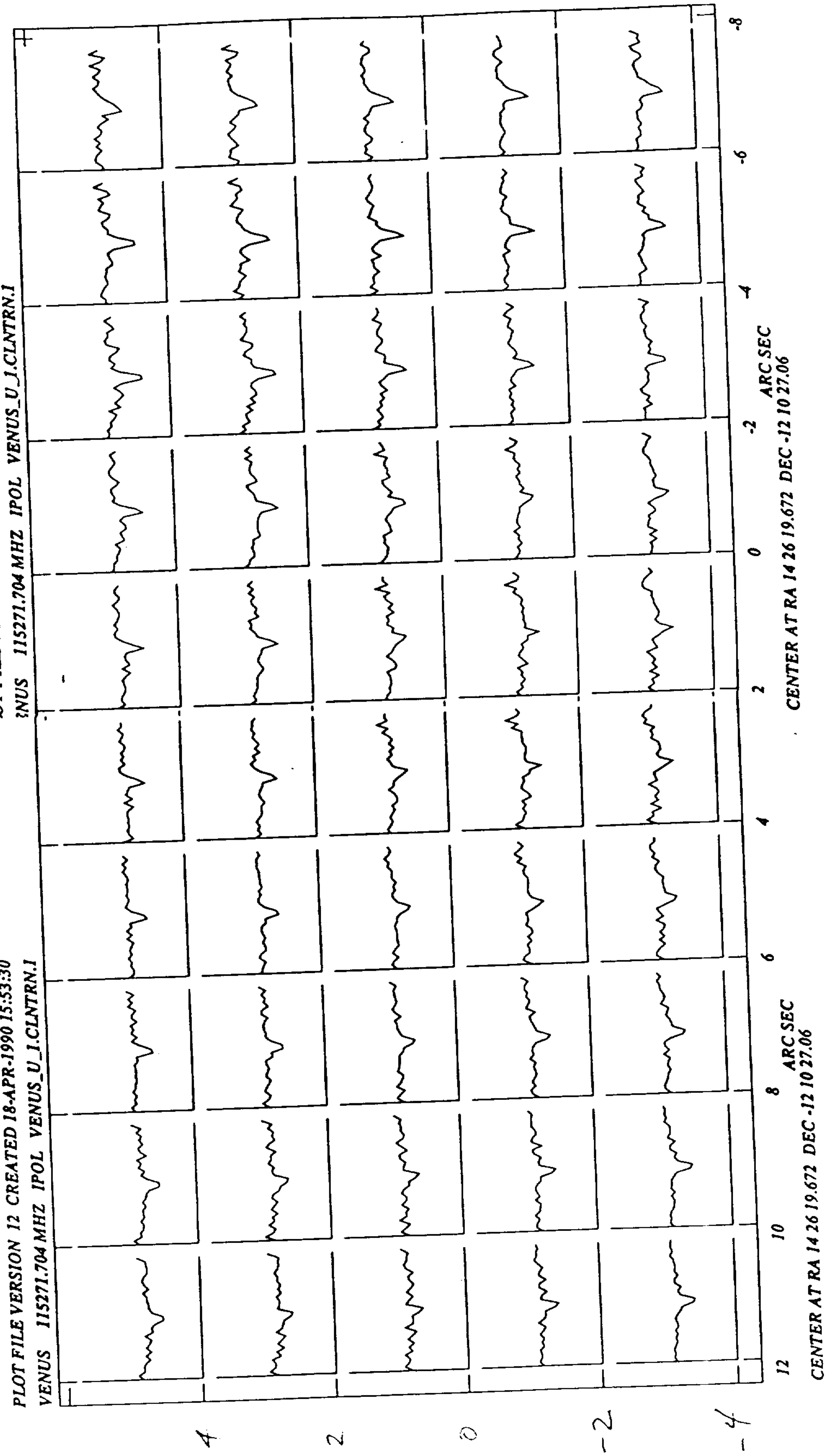
Titan is our most interesting source not only because it is the driver for the Cassini mission. The microwave lines of CO and HCN have been detected in this atmosphere. CO was first detected in the IR by B. Lutz, Toby Owens, and Catherine deBurge who fit their data with a CO tropospheric mixing ratio of 6×10^{-5} within a factor of about 2. Muhleman, Berge, and Clancy measured the 2.6 mm line (at OVRO) shortly after that and obtained a value of $6.5 \pm \times 10^{-5}$ for the mixing ratio assuming uniformly mixed CO from the surface to several hundred kilometers. The stability of the CO molecule under Titan's conditions STRONGLY argues that the mixing ratio should be nearly constant but perhaps increasing with altitude. Recently, the French group lead by Andre Martin measured the CO (0–1) line at IRAM and reported an order of magnitude less CO but, being convinced by the IR result, postulated that the mixing ratio falls with altitude. We, and the French, made new measurements in 1989. Our measurements (Muhleman and Clancy) were made in the submillimeter (2–3) transition at the CSO on Mauna Kea. A deliberately unsmoothed spectrum from that run is shown in Figure 7 along with a uniformly mixed model synthetic spectra. It can be seen from that figure that the problem is very difficult to resolve because the line is very broad — broader than any spectrometer that can be built! We feel that these results tend to confirm our original result and add no weight to the argument for the unintuitive decrease in the mixing ratio with altitude. Our group and the French group are Co-Investigators on the MSAR proposal to Cassini, which is a microwave spectrometer on the strawman payload. However, the main points of this controversy will be settled with Earth-based observations by both groups, independently. Unfortunately, the Europeans have a far more powerful telescope than any in the USA.

Fig 1. Map of Venus with the CO spectrum from each cell plotted at the spatial position of that cell. Spectra are line-continuum ratios.



1986 Observations

Fig 2. Venus line-to-continuum ratio CO spectra along the equator.



1986 Observations.

Fig. 3 Equatorial CO (0-1) spectra of Venus.   Proprietary Information !

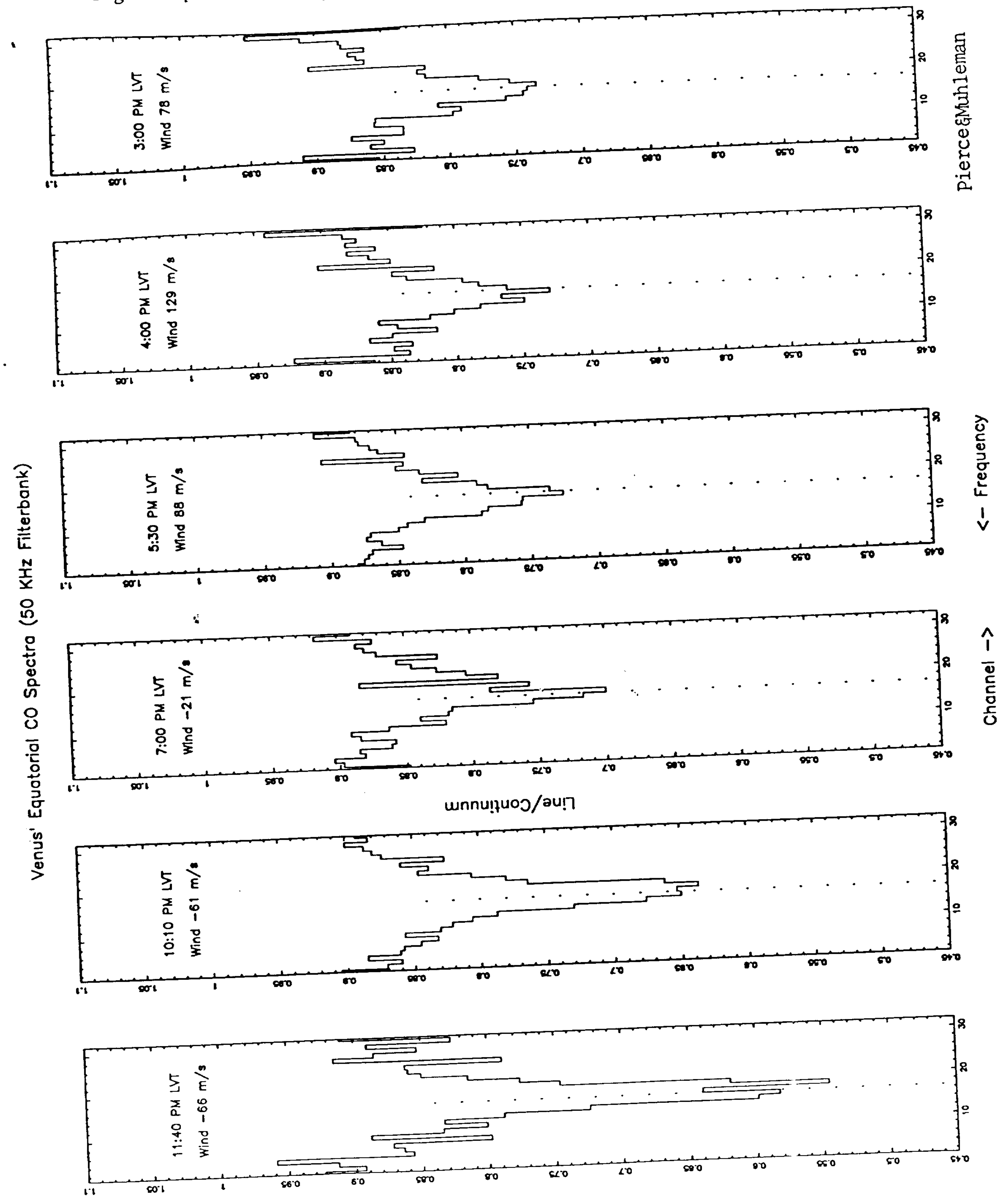
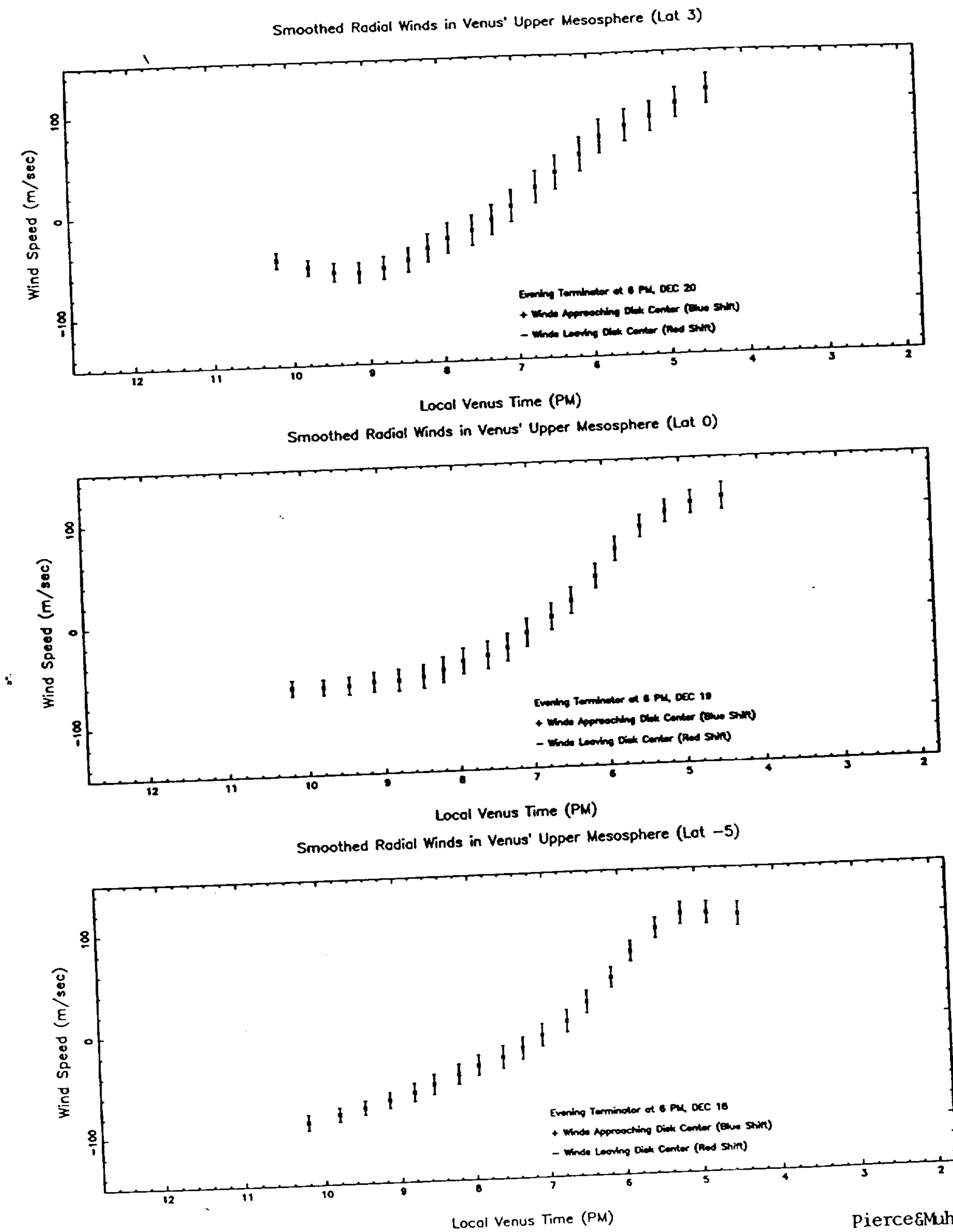


Fig 4. Measured doppler velocities in three Venus latitude bands.



Pierce&Muhleman

Fig 5. Winds over the Venus' limbs. Proprietary Information !

Pierce&Muhleman

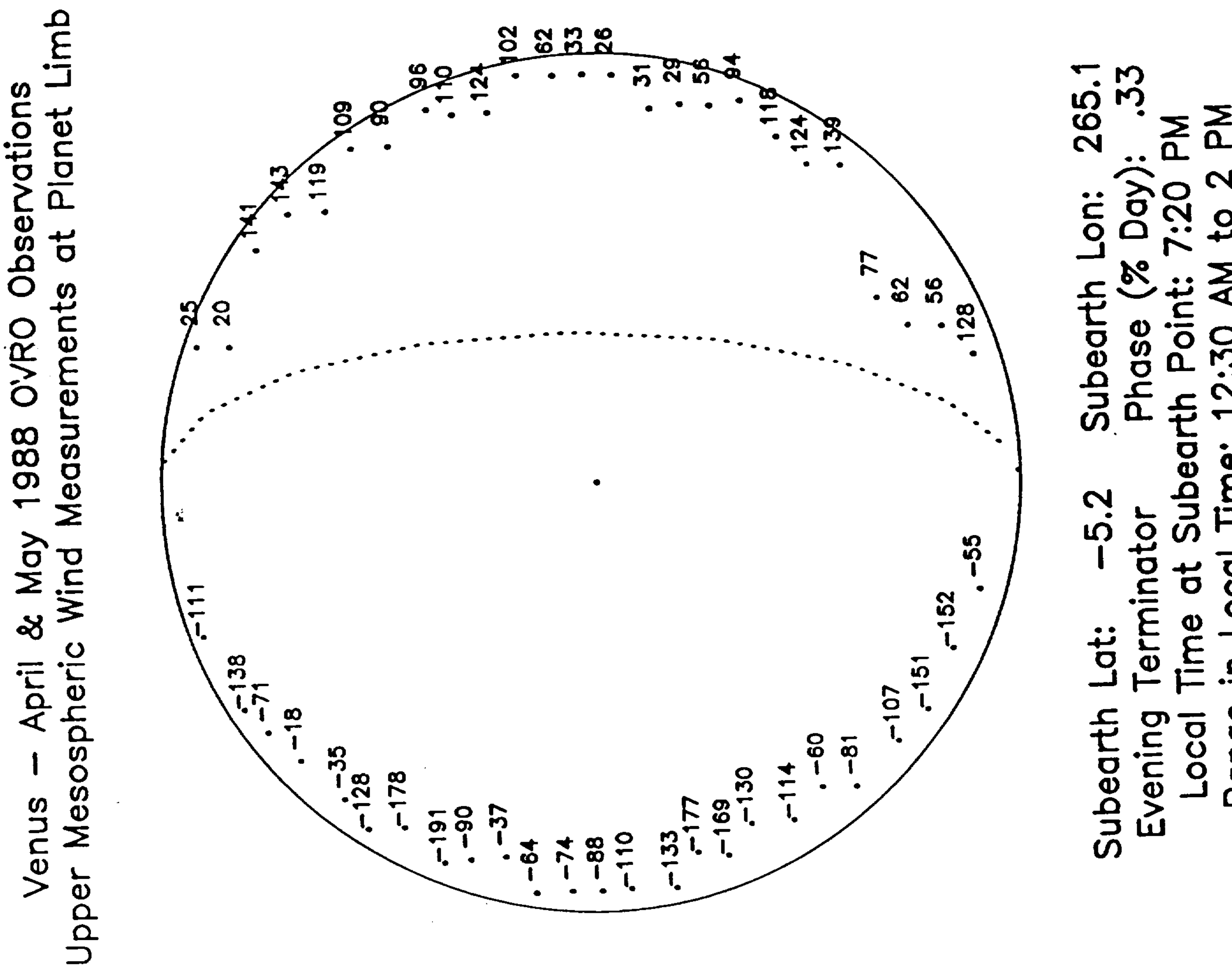
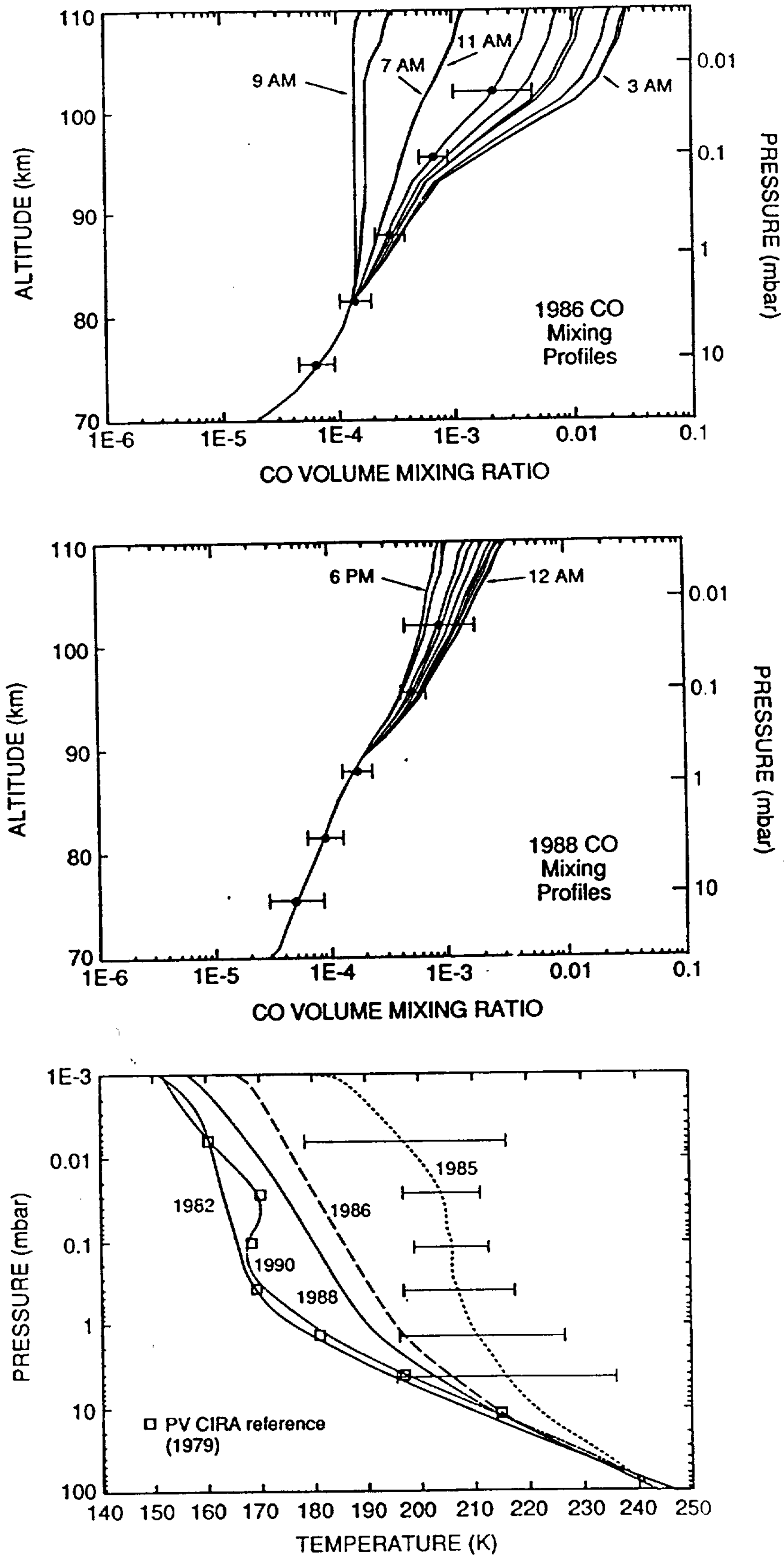


Fig. 6 Venus mixing ratio and Temp-Press profiles.

from Clancy & Muhleman (submitted to ICARUS)



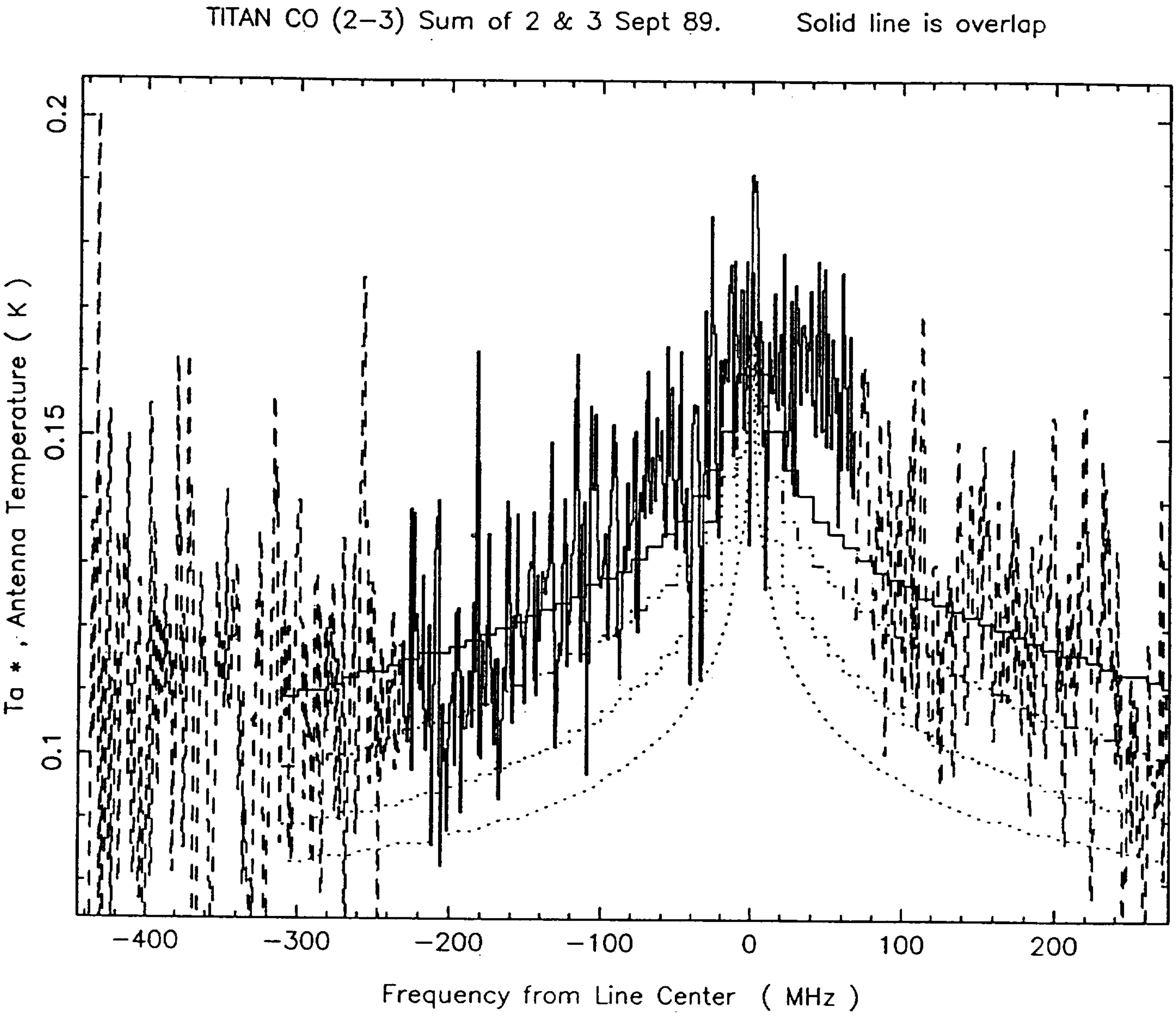


Fig. 7 . Unsmoothed composite spectra of the Titan CO (2-3) Transition. Smoothing removes the signicicant spike at 0 MHz. Model spectra : lowest dotted line for mixing ratio = 5 x 10 (-6), followed by 1 x 10(-5), 3 x 10 (-5) and 6 x 10 (-5). There is concern about the absolute scale of Ta *.